IDEAS FOR FUTURE GPS TIMING IMPROVEMENTS

Capt Steven T. Hutsell, USAF
2d Space Operations Squadron
300 O'Malley Avenue Suite 41
Falcon AFB CO 80912-3041

Abstract

Having recently met stringent criteria for Full Operational Capability (FOC) certification, GPS now has higher customer expectations than ever before. In order to maintain customer satisfaction, and to meet the even higher customer demands of the future, the GPS Master Control Station (MCS) must play a critical role in the process of carefully refining the performance and integrity of the GPS constellation, particularly in the area of timing.

This paper will present an operational perspective on several ideas for improving timing in GPS. These ideas include the desire for improved MCS-USNO data connectivity, an improved GPS-UTC prediction algorithm, a more robust Kalman Filter, and more features in the GPS reference time algorithm (the GPS Composite Clock), including frequency step resolution, a more explicit use of the basic time scale equation, and dynamic clock weighting.

Current MCS software meets the exceptional challenge of managing an extremely complex constellation of 24 navigation satellites. The GPS community will never want to risk losing the performance and integrity that we currently have. The community will, however, always seek to improve upon this performance and integrity.

INTRODUCTION

The GPS community will never experience a period of accepted complacency. Customer demands for accuracy will continue to increase. The increasing dependence on GPS as the primary mechanism for precise time transfer incurs the expectation for extremely high reliability within the GPS architecture. The community is quickly understanding the need to delicately balance integrity with performance improvements.

The GPS Master Control Station (MCS) software plays an integral role in this balance. The current release, version 5.41, is largely responsible for GPS maintaining Full Operational Capability (FOC). Generating, integrating, testing, and installing over two million lines of code is not an easy task, to say the least, especially when this code is responsible for the command and control of a 24 navigation satellite constellation.

This paper focuses on an operational perspective of various methods the GPS community could consider for refining the measurement, estimation, and prediction of timing within the MCS software.

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MCS-USNO CONNECTIVITY

The United States Naval Observatory (USNO) is the official Department of Defense (DoD) source for precise time and time interval (PTTI) information. USNO provides the DoD reference for Coordinated Universal Time (UTC). Precise time transfer is one of the three very important missions of GPS, and GPS is the primary means to disseminate precise time to the vast majority of DoD time transfer users [6].

This rather great responsibility depends hugely on the interface between the 2d Space Operations Squadron (2 SOPS) and USNO. The interface control document, ICD-GPS-202, defines the working relationship between these two agencies. The GPS Joint Program Office (JPO) will soon publish an update to this 11-year old ICD [3].

The Time Transfer mission in GPS currently operates in a closed daily feedback loop, as described in figure 1. The MCS transmits UTC information in navigation uploads to all operational satellites. The satellites, in turn, broadcast estimates of the GPS-UTC bias and drift in subframe 4, page 18 of the navigation message. In order for the MCS to properly generate GPS-UTC correction parameters for broadcast, USNO must compare GPS's broadcast of UTC to the USNO Master Clock, and feed back this offset information to the MCS.

The USNO Download

USNO employs an authorized (keyed) GPS receiver, connected to the Master Clock, to monitor the GPS broadcast. USNO generates a smoothed measurement for each successive 13-minute track. These measurements contain estimates of, among other parameters, the offset of satellite time with respect to UTC, the offset of GPS time with respect to UTC, and the time transfer error, based on that single-satellite track [6].

Every day, at approximately 1500z, the MCS downloads a data file from USNO. This file contains roughly 160 of these smoothed 13-minute track measurements, along with daily averages of the constellation-wide GPS-UTC offset and time transfer error. The MCS uses Procomm, installed on a PC-based computer connected to a keyed modem, to execute the daily download.

Unlike the interfaces with most other outside agencies, the MCS's computer interface with USNO is not currently governed by formal configuration management. Various problems with the hardware, software, and even the communication lines can interfere, and have interfered, with the time transfer loop on dozens of occasions over the last several years. On 20 Oct 95, 2 SOPS and USNO installed more current hardware and software to ease the operational headache, but some challenges still exist today.

Additionally, because the MCS downloads the UTC information into a PC, operators must manually extract and enter information onto the MCS mainframe. This process is susceptible to human error, and restricts the ability to pump large quantities of data into the mainframe for processing. Human error, such as typing the GPS-UTC sign incorrectly, can be devastating. The inability to receive large quantities of data renders the MCS mainframe less capable of measuring the true GPS-UTC offset, and hence, less capable of *predicting* GPS-UTC for time transfer.

GPS-UTC PREDICTION

As alluded to earlier, MCS operators enter a daily estimate of GPS-UTC into the mainframe. USNO generates this estimate by mapping a least-squares fit onto 38 hours worth of their 13-minute smoothed measurements of GPS-UTC. We at 2 SOPS call this the daily UTCBIAS point. The MCS predicts GPS-UTC using only *two* daily UTCBIAS points. Using two data points only 24 hours apart for calculating the GPS-UTC drift does not make the best use of the available optimal estimation techniques that most of us are familiar with.

By piping USNO-smoothed measurement data directly into the mainframe, the MCS could take advantage of techniques to a) apply corrections for known observables, b) edit outliers, and c) Kalman Filter the USNO data for optimum GPS-UTC estimation and prediction.

2 SOPS and Det 25, Space and Missile Systems Center (SMC) are currently addressing two software change requests related to the above concerns.

A ROBUST KALMAN FILTER

The current MCS Kalman Filter estimates the ephemeris, solar pressure, and clock states for 25 satellites, and the clock states for five monitor stations. The MCS Kalman Filter is capable of estimating the phase, frequency, and frequency drift states for all operational clocks.

Systematics/Periodics

The Kalman Filter does not currently perform explicit estimation of 12- or 24-hour periodic terms for our clocks. During earth eclipse seasons, our spaceborne atomic clocks may exhibit significant periodics with amplitudes of several nanoseconds, due possibly to thermal and/or electromagnetic systematics. To a large extent, other degrees of freedom in the Filter, particularly the ephemeris and solar pressure states, can help to artificially compensate for satellite clock periodics--the eccentricity and solar pressure parameters can, many times, help to model the effects of these periodics. In counterpoint, however, many could argue that this same feature can open the door for ephemeris-clock cross-corruption.

Because the Operational Control Segment (OCS) uses only five monitor stations, the MCS can only monitor a GPS satellite for, at most, 22 hours a day. When monitor stations are undergoing maintenance, this visibility lessens dramatically. Not only does this lack of coverage prevent the MCS from ensuring the integrity of the constellation full-time, but it also restricts the MCS's ability to decouple ephemeris, solar pressure, and clock errors. More monitor stations could help to minimize this cross-corruption.

Currently, the MCS does not estimate troposphere height. The MCS is *capable* of tropospheric estimation, based on measurements corrected with environmental sensor data. Unfortunately, the environmental sensor data we receive from most of our monitor stations has historically been very inconsistent. Until we can realize acceptable reliability from our sensor data, we will continue to use fixed (default) values for troposphere height states. Improving tropospheric state estimation could help to remove much of what we commonly may see as 24-hour periodics.

A Fully Correlated Kalman Filter

What we know as the MCS Kalman Filter is actually an ensemble of several mini-Kalman Filters, known as partitions. Each partition can estimate the states of, a maximum of, *six* satellites. Each partition estimates the states of all monitor stations, and a partition reconciliation algorithm keeps these monitor station states consistent between the estimating partitions. The partitioned architecture significantly reduces the computational burden within the MCS mainframe [5].

In future architecture, 2 SOPS hopes to utilize a fully correlated Filter capable of estimating the states of *all* satellites. The current partition architecture works very well, but a fully correlated Filter could reduce some of the short-term noise caused by temporary deviations between the MS states of the respective estimating partitions. Advances in CPU capability will hopefully meet the extra burden imposed by a fully correlated Filter.

THE FUTURE GPS COMPOSITE CLOCK

GPS, like most timing systems, uses a reference time scale. GPS time is defined by the Composite Clock software, installed in June 1990. The Composite Clock presented a remarkable solution to the need for a stable, continuously operating reference against which all GPS ephemeris, solar pressure, and clock states are referenced. The GPS Composite Clock is largely responsible for time transfer performance and GPS time stability that are both exceeding specifications [1,5].

Five years of operational use of the Composite Clock have helped 2 SOPS learn how to best utilize its capability. Similarly, the same five years have given us ample time to create a wish list for extra features.

Frequency Step Resolution

MCS software algorithms have historically provided excellent visibility into clock phase discontinuities. Software version 5.41 alarms, displays, and rejects unacceptably large phase discontinuities. Frequency step detection has been more of a challenge, however [2].

At approximately 0200z, 21 Dec 94, the primary timing input for the Colorado Springs monitor station (COSPM) failed. Due to a technical error, in recovering from the failure, COSPM experienced a discrete frequency jump of, approximately, 1.25 E-12 s/s. Since COSPM, at the time, had a long-term weighting factor of about 20 % in the Composite Clock [1], GPS time experienced a run-off on the order of -22 ns/day, with respect to UTC, as a direct result of the discrete frequency jump.

The impacts of this run-off were significant. The Control Segment (CS) component of error in GPS Time Transfer, usually within ± 10 ns, jumped to -19 ns. Though -19 ns was smaller than the overall ICD-GPS-202 time transfer specification (at the time, 110 ns) [6], many important authorized users greatly depend on an error magnitude less than 25 ns. Had the COSPM jump been any larger, we could have seriously impacted many important users in late December 1994 (figure 2).

In addition to the time transfer error, the GPS-UTC divergence itself was also noteworthy. By the time the MCS had completely steered out the GPS-UTC frequency offset of -22 ns/day, the GPS-UTC phase offset had grown to as large as -257 ns, on 17 Jan 95. Again, though well inside the system specification of ±

1000 ns [6], -257 ns was a much larger magnitude than the typical offset (within ± 30 ns), and substandard to what the timing community should reasonably expect from the Control Segment (figure 3).

This incident revealed the need for improved integrity monitoring, and a better capability to handle frequency jumps. The new L-Band Monitor (LBMON) software, installed in February 1995, has greatly helped the MCS in *detecting* frequency steps. LBMON scans ranging measurements once every six seconds for anomalies, alerts operators when anomalies are discovered, and provides real-time plots of ranging errors. LBMON's anomaly detection algorithm employs qualifying, forward, and backward-in-time filters optimized for detecting phase and frequency changes.

Several real-world incidents have allowed LBMON the opportunity to validate its role in the MCS's integrity monitoring capability. For example, at approximately 1930z, 20 Mar 95, the operational Rubidium frequency standard on SVN36 experienced a discrete frequency jump on the order of -1.58 E-11 s/s, during a period of earth eclipse. On the previous GPS software release, this error would likely have only appeared as successive increases in the ranging measurement residuals, once every K-point (every 15 minutes). With this limited information, the operator would have had trouble properly identifying the nature of the satellite ranging error. In particular, the GPS analyst would *not* have been able to quickly a) determine if this were a phase error or a frequency error, b) minimize the ranging error experienced by users, or c) minimize the effect on the GPS Composite Clock. This type of corruption could possibly have progressed for over an hour before being properly characterized, under the older software.

Just 28 minutes after the jump, LBMON flagged SVN36's anomalous behavior. Subsequently, the Navigation Analyst viewed a display called NPLSVSUM, which shows the near-real time (once every six seconds) observed ranging error for one or more satellites. When displaying NPLSVSUM for SVN36, the navigation analyst noticed the rather discernible change in ranging error. (Figure 4 is an EXCEL re-construction using the NPLSVSUM display data).

Because the analyst visually noticed the unusual run-off in ranging error, he was able to quickly increase specified portions of the system covariance matrix. This expedient reaction allowed the Filter to lock on to SVN36's new characteristics, permitted the operators to quickly upload new clock estimates for satellite broadcast, and minimized the degradation to the GPS Composite Clock.

Of course, not all anomalies are detected as easily as in this particular case. For instance, the Control Segment won't necessarily have visibility into the anomaly, and, in many cases, the anomaly may not be as noticeable as the above. Nonetheless, LBMON now allows operators to have a better "seat-of-the-pants" grasp of some of the more significant satellite and monitor station problems that can occur. LBMON has given the MCS more capability to identify, analyze, and reconcile some types of frequency step anomalies.

Ultimately though, MCS analysts would benefit from software that, in addition to detecting frequency steps like the above mentioned, would also *automatically* reconcile the step. Software that could automatically compensate Kalman Filter state estimates and covariances would reduce the dependency on operator input--humans are only so reliable in terms of catching anomalies, and a frequency step is one of the more difficult anomalies to detect.

Dynamic *q*-ing

The GPS Composite Clock is an implicit ensemble of over 20 of GPS's spaceborne and ground-based atomic frequency standards. Clock weighting is implicitly defined by the state covariances located within

the functionality of the Kalman Filter. Covariances are primarily a function of the measurement noise, the number of measurements, and the continuous time update process noise (q) values.

Analysts have the freedom to change clock q values periodically. Once per quarter, 2 SOPS derives new qs using independent Allan Variance data from the Naval Research Laboratory (NRL). 2 SOPS has successfully performed this fine tuning since October 1994. By uniquely tuning satellite clock state estimation based on empirical data, representing the true performance of each clock, 2 SOPS, thanks to NRL and other agencies, has improved the one-day stability of GPS time by approximately 10 % [4].

This quarterly activity should be viewed only as a short-term initiative, however. Manually updating the data base q values for each satellite incurs the risk of potentially hazardous typographical errors. The more often we update the qs, the higher the risk. Ideally, we'd like software that automatically and dynamically updates these qs. Besides alleviating the risk associated with manual updates, dynamic q-ing allows the capability to expediently reduce the effective weighting of clocks that have begun to behave anomalously. Obviously, dynamic q-ing has its *own* risks. Most sophisticated time scale algorithms can perform this task safely, and when we can utilize such a capability in the future, we must ensure that the MCS's version is at least as safe as those on existing, proven time scale algorithms.

Using the Basic Time Scale Equation

One noted difference between the Composite Clock and other time scale algorithms is the issue of separate control for clock weighting. The MCS's qs actually serve a multi-role purpose. Primarily, MCS qs increase covariances during time updates, and hence, are integral to Kalman Filter estimation. As stated earlier, qs also effectively control the weighting of clocks within the implicit ensemble. Additionally, the MCS calculates the user range accuracy (URA) values broadcasted in the navigation message, using these qs.

Other time scale algorithms, such as A1(USNO), AT1(NIST), and KAS-2(TSC), explicitly generate system time, using a *version* of the following equation [8]:

$$\sum_{i=1}^{N} A_i X_i\langle t+\tau|t+\tau\rangle = \sum_{i=1}^{N} A_i X_i\langle t+\tau|t\rangle \ , \quad where \quad \sum_{i=1}^{N} A_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

X_i is the state vector of the corrected clock i, and A_i is the user-controlled weighting matrix for clock i. This equation essentially mandates that the weighted sum of the corrected clock states (at a time $t + \tau$) is equal to the weighted sum of the time scale algorithm's predictions (from t to $t + \tau$) for those same corrected clock states. The Composite Clock is defined *implicitly* within the workings of the MCS Kalman Filter, which is responsible for the immense task of sorting out ephemeris and solar pressure state error, as well as clock error. The Composite Clock is not explicitly controlled by this time scale equation [8].

Use of this time scale equation would introduce the ability to control the weighting of clocks independently of the effective Kalman Filter weighting. This would generate a more explicit ensemble time separate from the implicit ensemble time generated within the Composite Clock.

The weights for each clock (A_i, i = 1,2,.....N), could have the capability for both operator control and automatic control. Meaning, at the same time the system would be dynamically updating the weights, the operator would have the option to override and reduce the weight of any clock, for whatever reason.

The following example illustrates the utility of operator-controlled weighting. The MCS Kalman Filter operates under the premise of stochastic, optimal estimation. The currently operating Cesium frequency standard aboard SVN22 does not behave very stochastically, and therefore, somewhat violates a basic assumption of Kalman Filtering. SVN22 experiences frequency jumps on the order of -5 E-13 once every 45-64 days [7] (figure 5 is an EXCEL reconstruction using NRL data). When these frequency steps are removed, SVN22 has a 10-day stability of around 5 E-14. Unedited, the 10-day stability is around 9 E-14 (figure 6). Ideally, one would like to keep the Kalman Filter q-ed based on its average performance, but prevent the frequency steps from corrupting Kalman Filter estimation, and thus, from distorting the mean time scale. A separate time scale with user-controlled weights, along with automatic frequency step resolution and dynamic q-ing, could help to reach this ideal.

The GPS Composite Clock fulfills the need for a stable, continuously operating reference against which all GPS ephemeris, solar pressure, and clock states are estimated. Without the GPS Composite Clock, we would not have been able to realize the time transfer performance and GPS time stability that we currently experience [5]. When introducing these ideas for improving the Composite Clock in the future, we must be careful not to introduce software that could impose unacceptable risk, or generate operational problems caused by being too complex to understand and operate. Let's take what we have now, value its advantages, and *refine*.

CONCLUSION

The time transfer mission of GPS has gained increasing attention in recent years. We all continue to appreciate how much timing is the pivotal physical phenomenon that helps all three missions of GPS to realize their capabilities. Both from an accuracy and integrity perspective, we must not take our current capability for granted; rather, we must take advantage of the continually advancing PTTI technology, as well as CPU technology.

Hand in hand, these two can be combined to make long-term improvements to MCS software, with safety as the guiding principle. Now is the opportunity to apply our operational experience and lessons learned, and exercise consideration towards the above ideas for improving GPS timing performance in the future.

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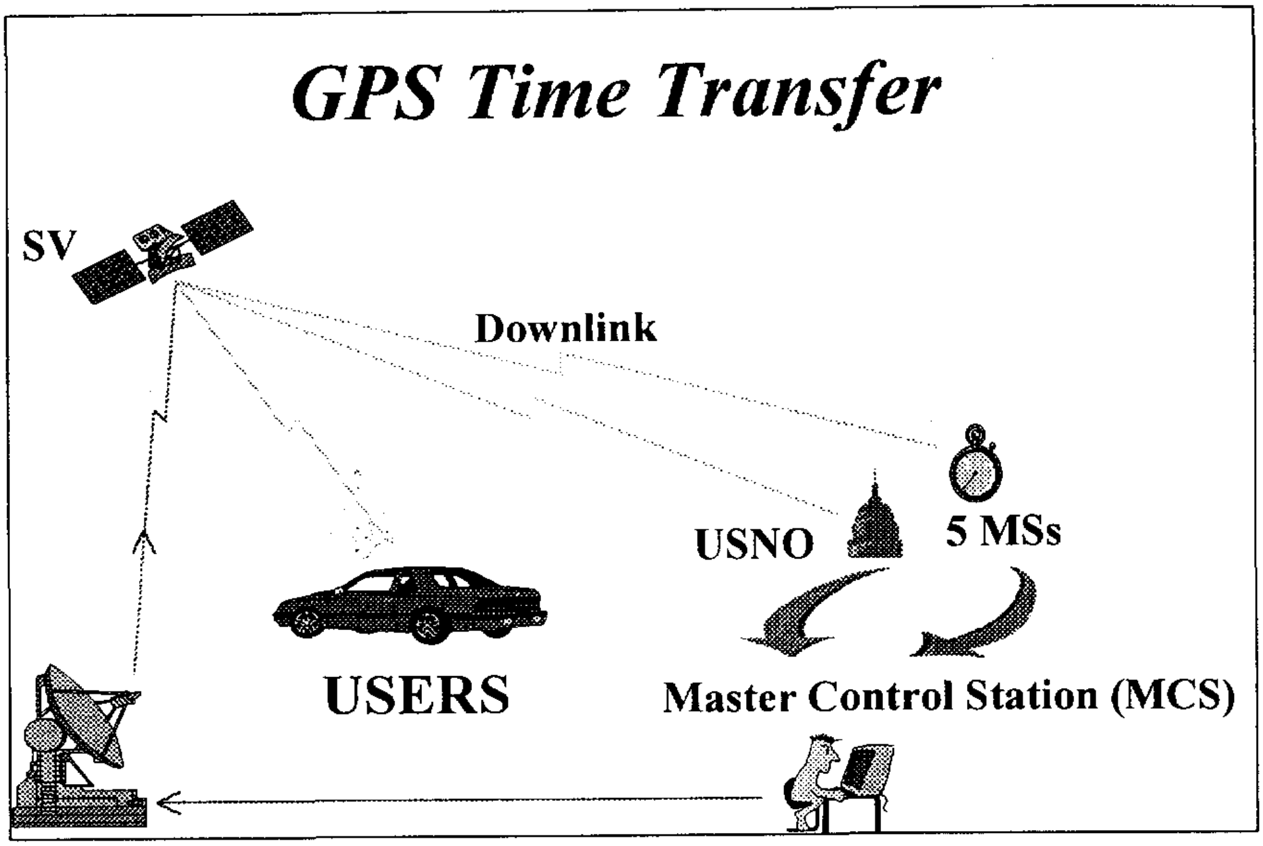

Figure 1

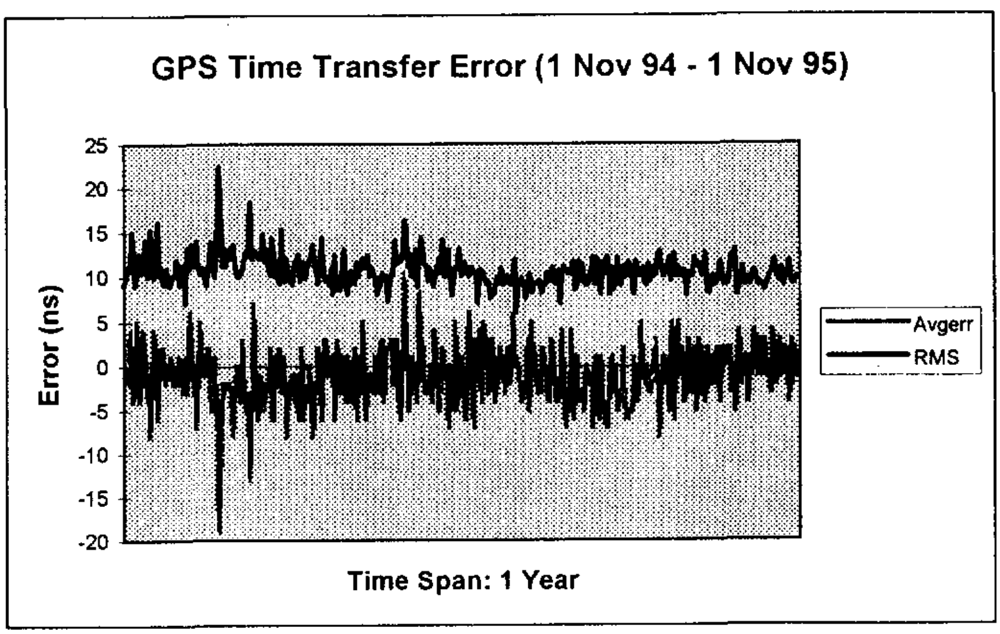

Figure 2

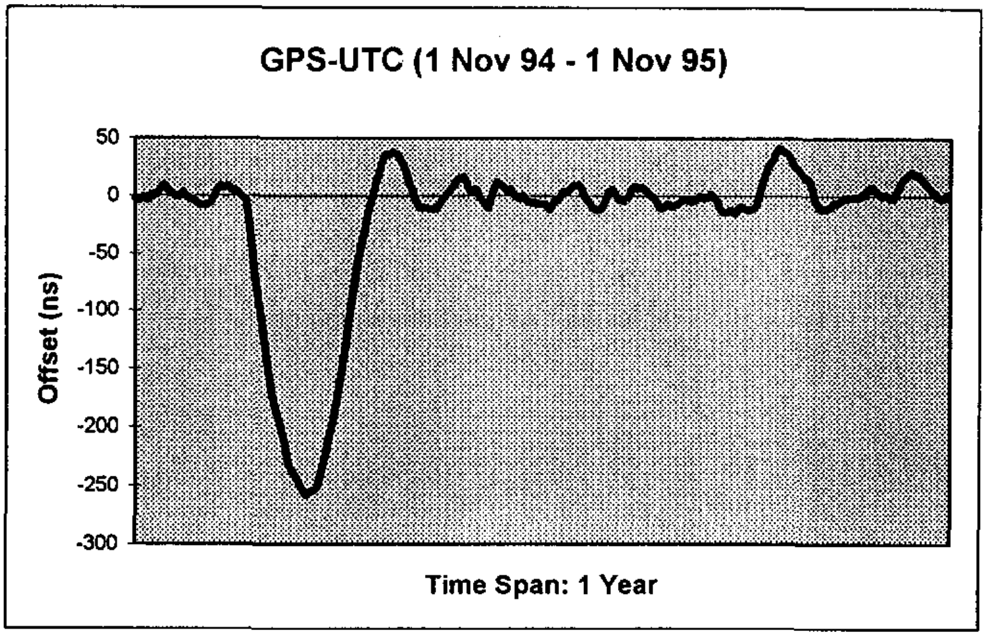

Figure 3

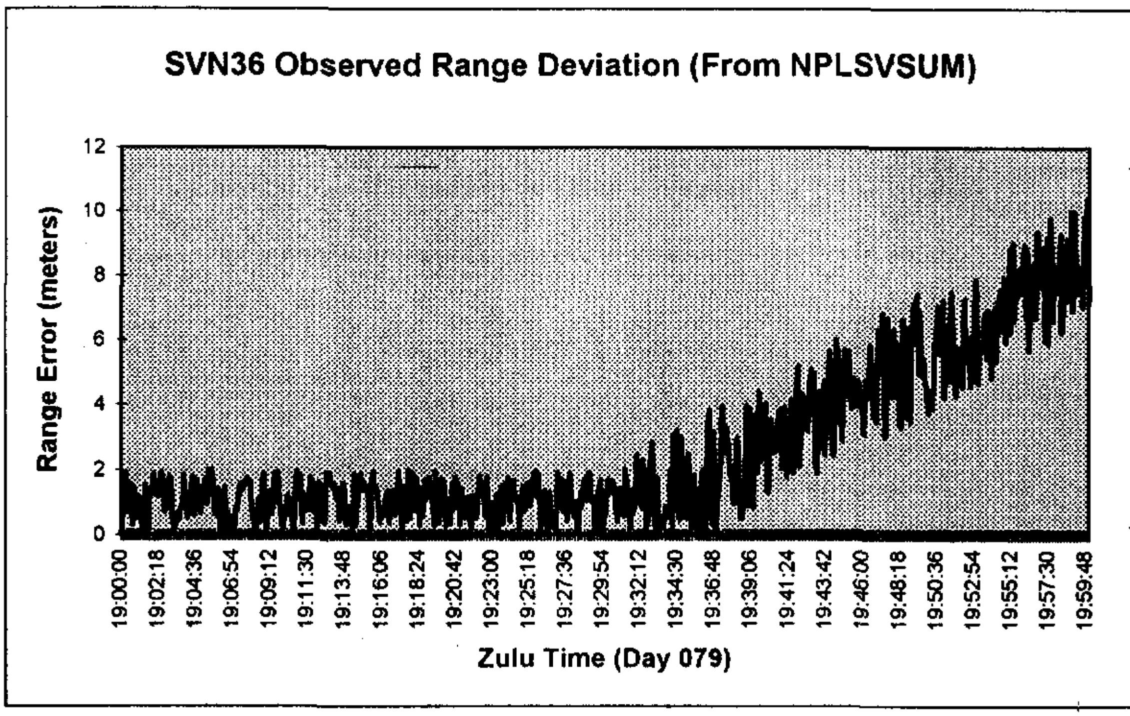

Figure 4

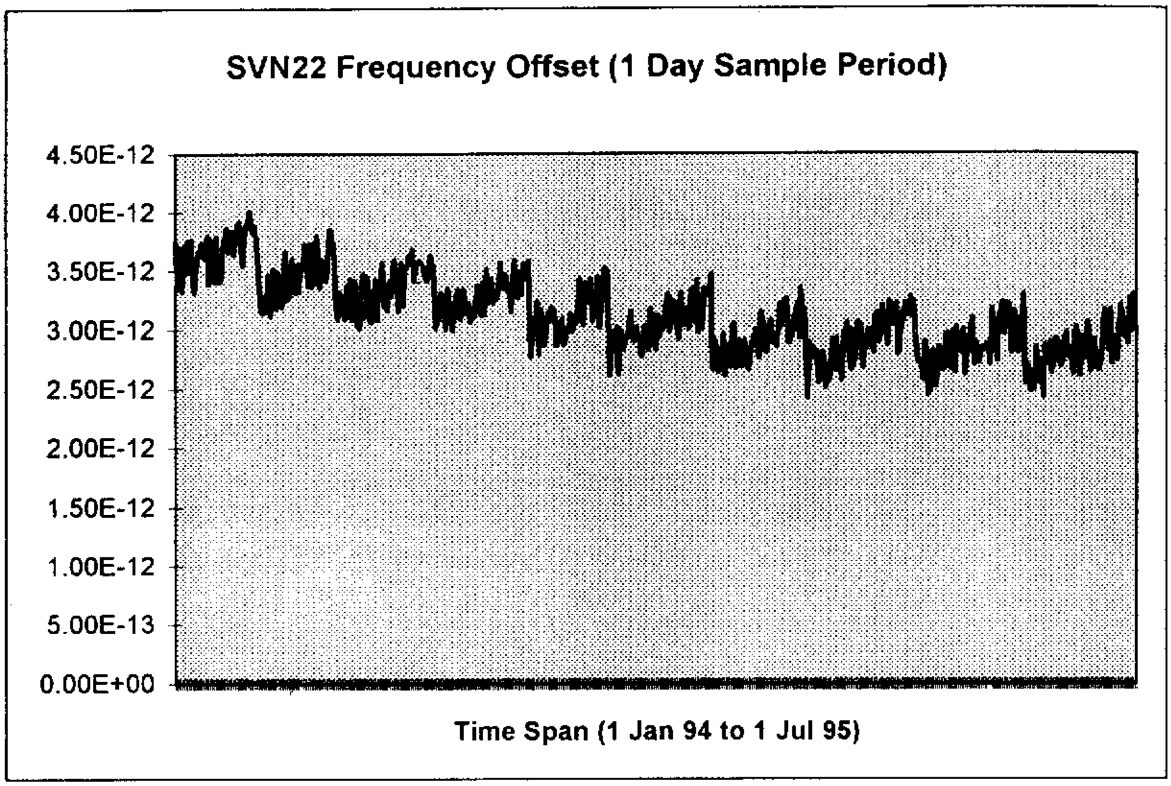

Figure 5

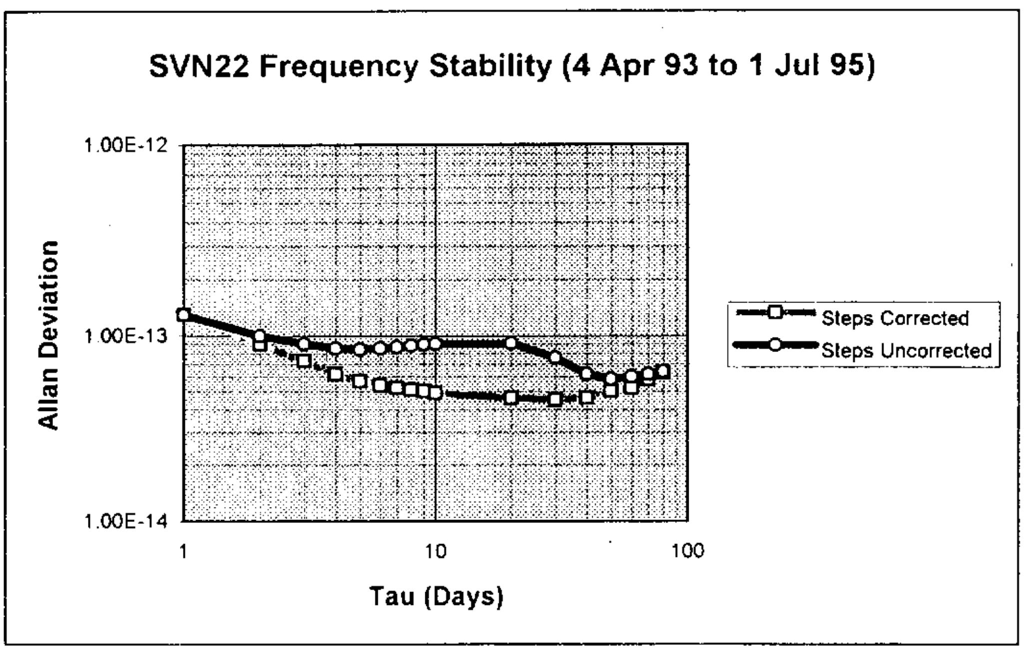

Figure 6

Questions and Answers

EDGAR BUTTERLINE (AT&T): As long as you were giving your Christmas wish list, I'd like to give you what I think is the number one item on the "civil users" Christmas wish list: Turn off SA.

As you know, and I realize you're not in a controlling position, the President has commissioned several blue ribbon civil commissions to come up with a recommendation for the use of GPS for civil users. And the last GPS Civil Users Conference, results of that blue ribbon panel was published and issued and discussed. On that list is "Turn off SA."

What are the prospects?

CAPT. STEVEN HUTSELL (USAF): I certainly am not in a position to answer that.

EDGAR BUTTERLINE (AT&T): Nothing is cooking as far as you know? And I realize you're not in a controlling position.

CAPT. STEVEN HUTSELL (USNO): I'm sure it's going to be a continuously-cooking matter. I'm sure it always comes up at both the Air Force Space Command level and the National Command Authority level. I can say that at the 2SOPS level at our squadron, we are really in no position to affect the decision; it's made at a much higher level than what we operate at. We are the implement.

EDGAR BUTTERLINE (AT&T): I understand, I understand. You're not making policy.

Let me make an offer. One of your big problems seems to be that telephone line. I really worry about that telephone line also; and if that telephone line happens to be an AT&T telephone line, let me give you my card. I assure you, I can get that fixed.

CAPT. STEVEN HUTSELL (USAF): Thankfully, with the backup that we have, I work with some very helpful people out at the Naval Observatory – when we do have communication problems, they're very helpful about getting the necessary information to us over the phone; and they help out on weekends and drive in, if necessary, to fix a problem.

But I complain about it a lot. We're not in seriously dire shape with that. But, it makes sense that in the long term we work on something that's a government-paid communication line and not something that we don't know for sure whether it's going to work or not.

WILLIAM KLEPCZYNSKI (USNO): In regard to the connectivity to the USNO, we are in the process of moving our alternate master clock out to Falcon. The first phase is sort of set up now and it's in operation there. And I'm sure that will go a long ways toward establishing better communications between Washington and Falcon; in addition to telephone lines, we'll be using satellite links and things like that. So there should be some improvement with time – and refinement.

CAPT. STEVEN HUTSELL (USAF): Right. It would offer, also, a good dual path for us in case if, for whatever reason, the connectivity is lost, we can always rely on a backup, whether it's the alternate master clock or Washington, D.C.